Near Earth Objects
Orbit Determination and impact Prediction

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Currently, there are approximately 300 comets and asteroids, or Near-Earth Objects (NEO'S), that can approach the orbit of the Earth to within 0.3 astronomical units. Because they are the links between the main-belt asteroids and the Earth's meteorites, these NEO'S are scientifically compelling objects. Before landing on the Earth's surface, each meteorite was a NEO, and most NEO'S originated in the asteroid belt between the orbits of Mars and Jupiter. In terms of landing a small spacecraft upon the surface of an interesting target body, some members of the NEO population arc more accessible than the moon itself. Because these objects can closely approach the 1 :arth, they often offer superb ground-based observation opportunities (including radar investigations). Some of the smaller NEO's routinely strike the Earth without consequence and while the collision of a large NEO with the Earth is an extremely unlikely event, it would have catastrophic consequences. Whether they are under investigation for scientific reasons, or as potential threats to the Earth, accurate orbits and ephemerides are an essential step in every phase of the NEO investigation process. Software packages built by P.W. Chodas have been used to investigate future close Earth approaches as well as the impacts of cm-net Shoemaker-Levy 9 with Jupiter **during** July 16-22, 1994.

Yeomans and Chodas (1994) have numerically integrated the motions of NEO'S with well determined orbits forward in time to A.D. 2200 and noted all future close Earth approaches. In each case, the best available initial orbits were utilized including those computed with radar, as well as optical data. Each object was integrated forward with Earth and moon perturbations treated separately, with general relativistic equations of motion and with perturbations by all planets at each integration step. For the active short-period comets whose motions are affected by the rocket-like effects of vaporizing ices, a nongravitational force model was employed. When a close approach to the Earth was sensed by the numerical integration software, an interpolation procedure was used to determine the time of the object's closest approach and the minimum separation distance at that time. The closest identified approach (to within 0.0057 AU of the Earth) was the October 2086 encounter with asteroid 2340 Hathor. For those objects making the closest Earth approaches in the next two centuries, an error analysis was conducted to determine whether or not the object's error ellipsoid at the time of closest approach included the Earth's position (i.e., an Earth collision could not be ruled out). Although there were no worrisome future encounters identified, a few asteroids and cornets will come close enough to the Earth to warrant monitoring (2340 Hathor, 4660 Nereus, cornet Finlay). The Aten type asteroid 2340 Hathor makes repeated close Earth approaches and because most of its orbit lies within that of the Earth, it is often a difficult object to observe in a dark sky. For both asteroids and comets, there are generally dramatic increases in their position uncertainties following close planetary encounters.

Because of their short observational data intervals, their unmodeled nongravitational effects, high relative velocities, and the possibility of escaping early detection by approaching the Earth from the sun's direction, long-period comets may present the largest unknown in assessing the long-term risk of Earth approaching objects. Fortunately the frequency with which these objects approach the Earth is very small compared with the numerous approaches by the population of near-Earth objects with short periodic orbits. For the short-period comets, rocket-like outgassing effects and offsets between the observed center-of-light and the comet's true center-of-mass can introduce large uncertainties in their long-term orbital extrapolations. The uncertainty in the future motion of an active short-period comet is substantially larger than the motion of an asteroid with a comparable observational history. While asteroids dominate the list of close Earth approaches in the next two centuries, their motions are relatively predictable when compared to the active comets.

The probability that a close Earth-approaching asteroid or comet will actually impact the Earth can be approximated via a procedure which examines the position error ellipsoid at the predicted time of closest Earth approach. The error ellipsoid is a representation of the scale and orientation of a 3-dimensional Gaussian probability density function. The probability that the object lies in a given region at a given time is simply the integral of the probability density function evaluated at that time over the volume of the region. If we take the region to be the figure of the Earth, this integral evaluation produces the probability that the object's position is within the Earth at the given time. (Here we ignore the dynamics associated with an impact) The result of this integral evaluation, however, is not the probability of impact, because it does not take into account the motion of the error ellipsoid past the Earth. The impact probability is the probability that the object's position will at any time lie within the figure of the Earth as it sweeps by the ellipsoid. The element of time may be removed from the impact probability computation by projecting the error ellipsoid into the plane perpendicular to the velocity vector of the Earth relative to the object. We will refer to this plane as the "impact" plane. The error ellipsoid then becomes an error ellipse which represents the marginal probability density function describing the probability that the object will at some time pass through a given point on the impact plane. To first order, the figure of the Earth projects into a circle in this plane; the probability of Earth impact is computed by simply integrating the marginal probability density function over the area of this circle.

While our software for identifying future Earth close approaches by near-Earth objects included the computation of impact probabilities, the lack of any very close Earth approaches consistently resulted in a zero probability. However, with the March 1993 discovery of cm-net Shoemaker-Levy 9 in orbit about Jupiter, our orbit determination software was used to determine with only a short observational data interval that the impact probability was larger than 90% - a figure that increased to greater than 99% as more astrometric data became available. The impact of comet Shoemaker-Levy 9 with Jupiter also provided a trial-by-fire test of the. software prior to, and during, the impact events themselves. The impact time predictions were accurate to within a few minutes. Among those quantities that were accurately predicted for the impacts of the cometary fragments with Jupiter were the Jovicentric latitudes (43-44 degrees south) and longitudes, the relative impact velocities (61 km/s), incipience angles (43 degrees), the Jovicentric longitudes relative to the midnight meridian (63 - 70 degrees), and the Earth-Jupiter-fragment angles (94 -99 degrees).

Reference:

Yeomans, D.K. and Chodas, P.W. (1994). Predicting Close Approaches of Asteroids and Comets to Earth. in Hazards Due to Comets and Asteroids, edited by Tom Gehrels. University of Arizona Press, Tucson, AZ (in press).